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14. ABSTRACT Work under the MURI in Ultracold Atom Optics Science and Technology has contributed substantially to the development of new technology and knowledge toward practical implementations of both ultracold matter and slow light systems. Work on cold matter focused on simplifying systems for producing Bose-Einstein condensation (BEC) and took studied both optical and atom chip based approaches. The chip-based approaches in particular have proved to enable substantial reduction in the size, weight and power of BEC systems. Work on slow light focused on the development of techniques for utilizing cold and ultracold atoms as the nonlinear optical medium to carry out electromagnetically induced transparency experiments.					
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## **Report Title**

Final Report: Multidisciplinary University Research Initiative on Ultracold Atom Optics

### **ABSTRACT**

Work under the MURI in Ultracold Atom Optics Science and Technology has contributed substantially to the development of new technology and knowledge toward practical implementations of both ultracold matter and slow light systems. Work on cold matter focused on simplifying systems for producing Bose-Einstein condensation (BEC) and took studied both optical and atom chip based approaches. The chip-based approaches in particular have proved to enable substantial reduction in the size, weight and power of BEC systems. Work on slow light focused on the development of techniques for utilizing cold and ultracold atoms as the nonlinear optical medium to carry out electromagnetically induced transparency experiments. Ultracold matter enables nonlinear optical interactions at the single photon level, which in turn provides a means to carry out work in quantum information processing. Highlights of the work include the first successful demonstration of atom interferometry on an atom chip, slow and stopped light, and demonstration of the first portable ultracold atom chip system. The work impacts several arenas of DoD interest, including technology for frequency standards and clocks, inertial sensing for navigation, mapping and geo-location, and information processing including quantum cryptography and communication.

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**List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

"Transverse heating due to non-adiabatic propagation of cold atoms in an atomic guide," Opt.Comm. 190/1-6, 231-237 (2001)

"Expansion of a Bose-Einstein condensate from a microtrap into a waveguide," Phys.Rev.A 65, 053612 (2002)

"Wave-function recombination instability in cold atom interferometers," Phys.Rev.A 66, 053601 (2002)

"Influence of nonadiabaticity and nonlinearity on the operation of cold-atom beam splitters," Phys.Rev.A 68, 013611 (2003)

"Decrease in the visibility of the interference fringes in a cold-atom accelerometer," Phys.Rev. A 69, 063611 (2004)

"Low-Light-Level Nonlinear Optics with Slow Light," Phys.Rev. A 68, 041801 (2003)

"Frequency Mixing Using EIT in Cold Atoms," Phys.Rev.Lett. 93, 183601 (2004)

"Generation of Paired Photons with Controllable Waveforms," Phys.Rev.Lett. 94, 183601 (2005)

"Storing and processing optical information with ultraslow light in Bose-Einstein condensates," Phys.Rev. A 70, 053831 (2004)

"Observation of Hybrid soliton vortex-ring structures in Bose-Einstein condensates," Phys.Rev.Lett. 94, 040403 (2005)

"High Flux source of Rubidium atoms," Rev.of Sci.Instruments 76, 103101 (2005)

"Detection of quantized conductance of neutral atoms near a charged carbon nanotube," Phys.Rev.Lett. 94, 066102 (2005)

"Observation of quantum shock waves created with ultracompressed slow light pulses in a Bose-Einstein condensate," Science, vol. 293 Issue 5530 pp.663 (2001)

"Observation of coherent optical information storage in an atomic medium using halted light pulses," Nature 409, 490-493 (2001)

"Wave mechanics of a two-wire atomic beamsplitter," Phys.Rev. A 69, 033607 (2004)

"Field linked states of ultracold polar molecules," Phys.Rev. A 69, 012710 (2004)

"Atom chip Bose-Einstein condensation in a vacuum cell," Phys.Rev. A, 70, 053606 (2004)

"An Atom Michelson Interferometer on a Chip Using a Bose-Einstein Condensate," Phys.Rev.Lett. 94, 090405 (2005)

"Efficient Loading of a Magnetic Waveguide on an Atom Chip," Phys.Rev.Lett. 94, 090405 (2005)

"Transistor-Like Behavior of a Bose-Einstein Condensate in a Triple Well Potential," eprint cond-mat/0607706

"Atomtronics: ultracold atom analogs of electronic devices," eprint cond-mat/0606625

**Number of Papers published in peer-reviewed journals:** 22.00

**(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)**

**Number of Papers published in non peer-reviewed journals:** 0.00

**(c) Presentations**

Atom optics with laser cooled atoms guided by magnetic fields from current carrying wires, Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference 2000 (CLEO/QELS), San Francisco, CA, May 2000

Magnetic Guides and Neutral-Atom Beamsplitter, DAMOP 2000, Storrs, CT., June 2000

Towards Integrated Atom-Optics for inertial measurements, Sandia Laboratory, Albuquerque, NM, August 2000

Ultracold Atom Optics Science and Technology, DOD, MURI workshop on ultracold atom science, Adelphi, MD, November 2001

Atom Hoses and Waveguides, University of Colorado, JILA, November 2001

Ultracold Atom Optics Science and Technology, DOD, MURI Review on ultracold atom science, Boulder, CO, November 2002

Integrated Atom Optics, Colloquium, University of Arizona, Tucson, AZ, February 2002

Experiments with an atom chip BEC beamsplitter, DAMOP, Boulder, CO, May 2003

Integrated Atom Optics, DARPA PINS Pre-BAA workshop, Arlington, VA, May 2003

Integrated Atom Optics, Sarnoff Corporation physics seminar, December 2003

Atom Chip Bose-Einstein condensation in a portable vacuum cell, CLEO, San Francisco, CA, May 2004

Optical beam splitter integrated on a magnetic atom chip, CLEO, San Francisco, CA, May 2004

DARPA Precision Inertial Sensing Program 2004 PI Review, Monterey, CA, December 2004

Review of the Research Activities of the MURI Collaboration, MURI Army Research Office Atom Optics Annual Review, Stanford, CA, March 2004

Integrated Atom Optics, Department of Physics Colloquium, Texas A&M University, College Station, TX, May 2004

BEC Waveguide Michelson Interferometer on a Chip, Institute for Theoretical Atom, Molecular and Optical Physics Quantum Degenerate Gases in Low-Dimensionality Workshop, Cambridge, MA, October 2004

Business Opportunities of Ultracold Atoms, Venrock Corporation, New York, NY, June 2004

Ultracold atom enabling technology, Rockwell Scientific Company Seminar, Los Angeles, CA, January 2004

Ultracold atom enabling technology, DARPA Precision Inertial Sensing (PINS) workshop, Charleston, SC, January 2004

DARPA Atomtronics Kickoff, Boulder, CO, September 2004

An Atom Michelson Interferometer on a Chip, DAMOP, Lincoln, NE, May 2005

An Atom Michelson Interferometer and Atom Chip Technology, Atomic, Molecular and Optical Science Seminar, University of California, Berkeley, CA, March 2005

An Atom Michelson interferometer and Atom Chip Technology, Center for Ultracold Atoms, Massachusetts Institute of Technology, Cambridge, MA, April 2005

An Atom Michelson Interferometer and Other Stories of Atom Chips, Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA, November 2005

An Atom Michelson Interferometer and Atom Chip Technology, Department of Electrical Engineering, University of Colorado, Boulder, CO, February 2005

Perspectives from neutral atom traps, NIST Workshop on Trapped Ion Quantum Computing, bBoulder, CO, February 2006

Number of Presentations: 26.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT SUPPORTED
Shengweng Du	0.50
Matt Squires	0.50
Kurt Miller	0.50
Steven Segal	0.50
N. Blanchard	0.25
James Stickney	0.50
Pavel Kolchin	0.25
Danielle Braje	0.40
V. Balic	0.40
S. Goda	0.25
Naomi Ginsberg	0.25
Anne Goodsell	0.25
Trygve Ristoph	0.25
Michael Budde	0.25
Laurent Vernac	0.25
Zachary Dutton	0.40
Christopher Slowe	0.40
FTE Equivalent:	6.10
Total Number:	17

Names of Post Doctorates

NAME	PERCENT SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Carl Wieman	0.00	Yes
Cornell, Eric	0.00	Yes
Steve Harris	0.08	No
Lene Hau	0.08	No
Dana Anderson	0.08	No
Alex Zozulya	0.08	No
Victor Bright	0.08	No
John Bohn	0.08	No
Deborah Jin	0.00	Yes
<b>FTE Equivalent:</b>	<b>0.48</b>	
<b>Total Number:</b>	<b>9</b>	

### Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
William Holmgren	0.50
Lynsi Aldridge	0.50
Farhad Majdeteimour	0.50
Allison Churnside	0.40
Kevin Suhr	0.30
Jesse Smock	0.30
Matt Hayman	0.50
Carl Wiedeman	0.50
Meagan Hart	0.50
<b>FTE Equivalent:</b>	<b>4.00</b>
<b>Total Number:</b>	<b>9</b>

### Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 4.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 0.00

### Names of Personnel receiving masters degrees

NAME

**Total Number:**

### Names of personnel receiving PHDs

NAME

Shengwang Du

Matt Squires

Danielle Braje

James Stickney

**Total Number:****4****Names of other research staff**NAMEPERCENT SUPPORTED

Ashley Savage

0.75 No

Leslie Czaia

0.50 No

Erica Mady

0.75 No

**FTE Equivalent:****2.00****Total Number:****3****Sub Contractors (DD882)**

1 a. Stanford University

1 b. Office of Sponsored Research

Board of Trustees of the Leland Stanford

Stanford CA 94305

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Worcester Polytechnic Institute

1 b. Office of Sponsored Programs

Worcester Polytechnic Institute

Worcester MA 016092280

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Worcester Polytechnic Institute

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Worcester MA 01609

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Stanford University

1 b. Office of Sponsored Research

Mail Stop 4125, Room 110

Stanford CA 943054125

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Harvard University

1 b. Harvard Medical School

Nrb 255

Boston

MA

02115

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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1 a. Harvard University

1 b. Harvard Medical School

Nrb 255

Boston

MA

02115

**Sub Contractor Numbers (c):**

**Patent Clause Number (d-1):**

**Patent Date (d-2):**

**Work Description (e):**

**Sub Contract Award Date (f-1):**

**Sub Contract Est Completion Date(f-2):**

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**Inventions (DD882)**

This MURI on Ultracold Atom Science and Technology began four years after the first demonstration of Bose-Einstein condensation (BEC) in an atomic vapor. Recognizing the enormous potential of BEC and other forms of ultracold matter, this MURI was the first effort in the United States focused on its practical implications. Two years after the start of this work, the 2001 Nobel Prize in physics was awarded to Carl E. Wieman and Eric Cornell, two investigators on this MURI, and to Wolfgang Ketterle, an investigator on another, related MURI team. Since then, many honors have been awarded to researchers of this MURI for their fundamental contributions to the field of ultracold matter. And, correspondingly, this MURI work has played a key role in many of the outstanding achievements of the field over the life of the effort.

Here, “cold matter” refers to a state of matter in which the constituent particles are extremely cold, typically well less than 1 mK, but whose behavior is nevertheless adequately described by the laws of thermodynamics. A gas of alkali atoms can be readily brought to these cold temperatures using laser cooling techniques developed in the late 1980’s and early ‘90’s (and for which the 1997 Nobel Prize was awarded.) “Ultracold matter” refers to a state in which a collection of identical particles must be described using the laws of quantum mechanics, and the state of the matter itself is characterized in terms of a quantum mechanical wavefunction.

The BEC is often pointed to as the atom analog of the laser. Among other aspects, ultracold matter has wavelike properties and “atom optics” provides for numerous analogs to laser based devices and systems. Yet unlike photons, atoms have mass and can interact. Moreover, atoms come in a large variety of species, and depending on their spin, interact either as bosons or fermions, leading to very different properties. Thus the domain of ultracold atoms is in fact vastly richer than that of light, and therefore also rather more intricate, as a field of research.

From the perspective of atom optics, one can appreciate the potential of ultracold atoms in practical applications. Indeed, the potential utility of atoms is very real in many arenas of DoD interest. These include inertial sensing for guidance, navigation, mapping, geo-location, and gravimetry; timing for frequency standards and clocks; and magnetic field sensing. As a quantum state, ultracold matter has unique potential in quantum communications and encryption, and possibly in quantum computing.

This MURI has focused specifically on the practical aspects of ultracold atoms technology: to emphasize areas of research that clarify the key principles at play in sensing applications, for example. Moreover, the MURI work has been intent on simplifying the route to ultracold atoms; to make for smaller, more practical systems.

MURI-Supported research over its life has led to several “firsts” including the first atom Michelson interferometer on a chip, the first portable BEC atom chip system, and the first Molecular BEC. It also led to substantial progress in slow light and related applications of electromagnetically induced transparency (EIT), including the stopping of light. We now highlight some of the work and findings that arose in the final portion of the MURI research.

It is of general interest to understand various classes of nonlinear dynamical phenomenon in BEC’s. For example, L. Hau’s earlier MURI-supported work on slow light demonstrated the

ability to store and processes optical information in a Bose-Einstein Condensate. Further work has led to the experimental discovery of compound structures comprising solitons and vortex rings in BEC's. Hau and collaborators examined both their creation via soliton-vortex collisions, and their subsequent dynamical development, which is largely governed by the dynamics of interacting vortex rings. They were able to develop a theoretical model in three-dimensional cylindrical symmetry, which rather accurately modeled the observed behavior.

Atom fluxes utilized in typical BEC interferometry experiments are typically small, on the order of  $10^3$  to  $10^4$  atoms/s. Moreover in many experiments of interest, such as those involving quantum computing and QED experiments, utilize a single atom. Therefore it is of interest to develop very efficient, often single atom, detectors. Hau and collaborators describe a novel single atom detector that uses the high electric field surrounding a charged single-walled carbon nanotube to attract and subsequently field-ionize neutral atoms. A theoretical study of the field-ionization tunneling rates for atomic trajectories in the attractive potential near a nanowire shows that a broadly applicable, high spatial resolution, low-power, neutral-atom detector with nearly 100% efficiency is realizable with present-day technology. Calculations also show that the system can provide the first opportunity to study quantized conductance phenomena when detecting cold neutral atoms with mean velocities less than 15 m/s.

In other arenas, it is photons rather than atoms, that carry information of interest. For applications of quantum communication and cryptography, sources of entangled pairs of photons are of particular interest. To this end, S.E. Harris and collaborators carried out experimental and theoretical work showing the generation of counter-propagating paired photons with coherence times of about 50 ns and waveforms that are controllable at a rudimentary level. Using cw lasers, electromagnetically induced transparency and cold  $^{87}\text{Rb}$  atoms they generated paired photons into opposing single-mode optical fibers at a rate of 12 000 pairs per second. Because they are narrow band, paired photons that are generated by this technique should be useful for transferring correlated and entangled momenta to cold atoms.

For many years, spontaneous parametric down-conversion in nonlinear crystals has become the near standard method for generating correlated and entangled photon pairs. These paired photons are routinely used in areas such as quantum measurement, imaging, and information transfer. The existing sources of paired photons have limitations for certain applications: (a) their linewidth is too broad, and their spectral brightness is too low to allow excitation of atomic species; (b) because their coherence time is in the subpicosecond range, photon waveforms are not resolvable by existing photodetectors; and (c) their short coherence length, 100  $\mu\text{m}$ , is prohibitively small for long distance quantum communication. Following the field-opening works of Lukin (at Harvard) and Kimble (at Caltech) groups, MURI work led to a source of paired photons that decisively overcomes the aforementioned limitations. This source makes use of slow light with a variable group velocity thereby allowing the control of the width, and to some extent, of the shape of the quantum wave packet.

MURI-supported research has led to a DARPA supported program in cold atom based inertial sensors. As the MURI project comes to a close, much of the technical effort is augmented by a DARPA effort supporting the development of atom chip technology for inertial navigation applications. Indeed, it can be said this MURI led to DARPA's interest and funding in this

arena. In any case, the atom chip related work reported here is also partially supported under the DARPA PINS program.

Cornell and Anderson's work on an atom chip interferometer succeeded in demonstrating a 10 ms coherence time. Roughly speaking, the signal-to-noise performance of cold-atom sensors will improve linearly as the coherence time becomes longer. Long-term targets seek coherence time of 100 ms to 1000 ms. It has been unclear whether the guiding experiments coherence times had been limited by technical or fundamental phenomena. For that reason, Alex Zozulya carried out a theoretical analysis of the experiment, showing that under certain circumstances coherence time could be limited by slow atomic collisions. The latter work is a guide to further experiments, in which we have already shown that coherence times can be greater than 100 ms.

The last interim report described Anderson's demonstration of a BEC in a small, portable vacuum cell. Two major steps have taken place since then: first, the size of the system has been further reduced –the vacuum system can be held in one hand. Second, we eliminated all epoxy from the cell construction. This should lead to much longer lifetimes for the vacuum integrity of the UHV cells. The epoxyless construction is enabled by anodic bonding between the silicon atom chip and the pyrex cell of the vacuum system. Electrical connections to the chip are made possible by a new UHV compatible process of forming electrical vias through the atom chip. Using this new technology we successfully demonstrated atom guiding around a curve in one of our portable vacuum systems.

In earlier work Wieman's group investigated the control of atom-atom interactions through Feshbach resonances. Recently the spontaneous dissociation of  $^{85}\text{Rb}$  dimmers in the highest lying vibrational level has been observed in the vicinity of the Feshbach resonance, which was used to produce them. Feshbach resonances allow one to control the collisional interaction among pairs of atoms using a magnetic field. In fact, they have provided a means to produce and study ultracold molecules. In this contract period, Dr.'s Wieman, Cornell, and Jin published a systematic study of the production efficiency of ultracold Feshbach molecules in both bosonic and fermionic systems. Feshbach resonance techniques have proven to be very powerful and in particular, led MURI researcher Dr. Debbie Jin to observe cooper pair formation in a degenerate Fermi gas of ultracold atoms.

Harris's group has looked at electromagnetically induced transparency (EIT) in an optically thick, cold medium; the cold medium creates a unique system where pulse-propagation velocities may be orders of magnitude less than  $c$  and optical nonlinearities become exceedingly large. As a result, nonlinear processes become very efficient at low light levels. Harris has, in fact, now studied frequency mixing in ultracold atoms using EIT techniques. In this period, the Harris group significantly demonstrated the generation of paired photons with controllable waveforms. The significance lies in the utility of paired photons in quantum cryptography and quantum computing.

In a related vein, Hau's group demonstrating the storing and processing of optical information using ultra-slow light in BEC's.